National Aeronautics and Space Administration

YEARS 1-3 ***EXECUTIVE SUMMARY***

Center for Lunar Origin and Evolution (CLOE)

PI: William Bottke (SwRI)

NASA LUNAR SCIENCE INSTITUTE

Executive Summary
Progress Report for the Center for Lunar Origin and Evolution (CLOE)
NASA Lunar Science Institute
PI: Dr. William Bottke
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The dramatic Apollo exploration of the Moon concluded in the early 1970s. Three fundamental scientific concepts emerged from this historic venture that profoundly changed our understanding of how objects like our Moon form and evolve. These ideas, as identified by the National Research Council's 2007 Space Studies Board report, "The Scientific Context for the Exploration of the Moon" (hereafter the *SSB Report*), are:

(SB-A) Lunar origin by giant impact,
(SB-B) The existence of an early lunar magma ocean, and
(SB-C) The potential of an impact cataclysm at 3.9 billion years ago (Ga).

These themes related to the top SSB Report science goals**,** which were ranked in priority order. We list the top ones that are directly relevant to the work described in this summary.

- (1a) Test the cataclysm hypothesis by determining the spacing in time of the creation of lunar basins.
- (1b) Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin)
- (1c) Establish a precise absolute chronology
- (1d) Assess the recent impact flux

In addition, last year the Decadal Survey report "Vision and Voyages for Planetary Science in the Decade 2013-2022 (hereafter Decadal Survey)" was published by NASA/NRC. This work organized the central questions of planetary science into three cross-cutting themes, *Building new worlds* (the understanding solar system beginnings), *Planetary habitats* (searching for the requirements for life, and *Workings of solar systems* (revealing planetary processes through time). Several of the central, guiding questions from these themes are described below:

(DS-A) What were the initial stages, conditions and processes of solar system formation and the nature of the interstellar matter that was incorporated?
(DS-B) How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?
(DS-C) What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?
(DS-D) What solar system bodies endanger and what mechanisms shield Earth's biosphere?

Our NASA Lunar Science Institute, the multi-institutional *Center for Lunar Origin and Evolution* (CLOE), was ***specifically designed*** to address the critical questions described above, namely by exploring not only how our planetary system formed and evolved but also how this record bears on both the geophysical/geochemical make-up of the Moon and the lunar cratering record. Moreover, our work takes advantage of constraints from other worlds (e.g., Earth, asteroids) that can be used to tell the story of the inner solar system. In other words, our goals are (i) to use the Moon to tell us about the origin and history of the rest of the solar system, and (ii) to use the solar system to inform us on how the Moon formed and evolved. *This makes CLOE highly relevant to more than just lunar research, but to the **biggest issues faced by planetary science**.*

Here we briefly describe the progress that has been made over CLOE's scientific research themes. In the beginning of each section, we will also highlight the central questions above that have been addressed by our work from 2009-2012.

Theme 1: Formation of the Moon

In Theme 1, we are modeling the evolution of the moon from its origin in a giant impact (GI) on Earth through to the end of the Moon's accumulation. Here we describe new numerical results that directly bear on and will help validate, or invalidate, the widely accepted giant impact model of the Moon's formation. ***In this section, we address questions (SB-A), (DS-A), (DS-C), and we determine the initial thermal state of the Moon, which informs (SB-B).***

We have performed the highest resolution simulations to date of Moon-forming impacts, and have conducted the first detailed comparisons between impact simulations conducted with the Lagrangian hydrocode SPH and the Eulerian hydrocode CTH (Canup et al. 2012; Figure 1). We find that both methods produce comparable results: that the oblique, low-velocity impact of a roughly Mars-size body with the Earth can produce an appropriately massive protolunar disk and the correct initial spin rate for the Earth.

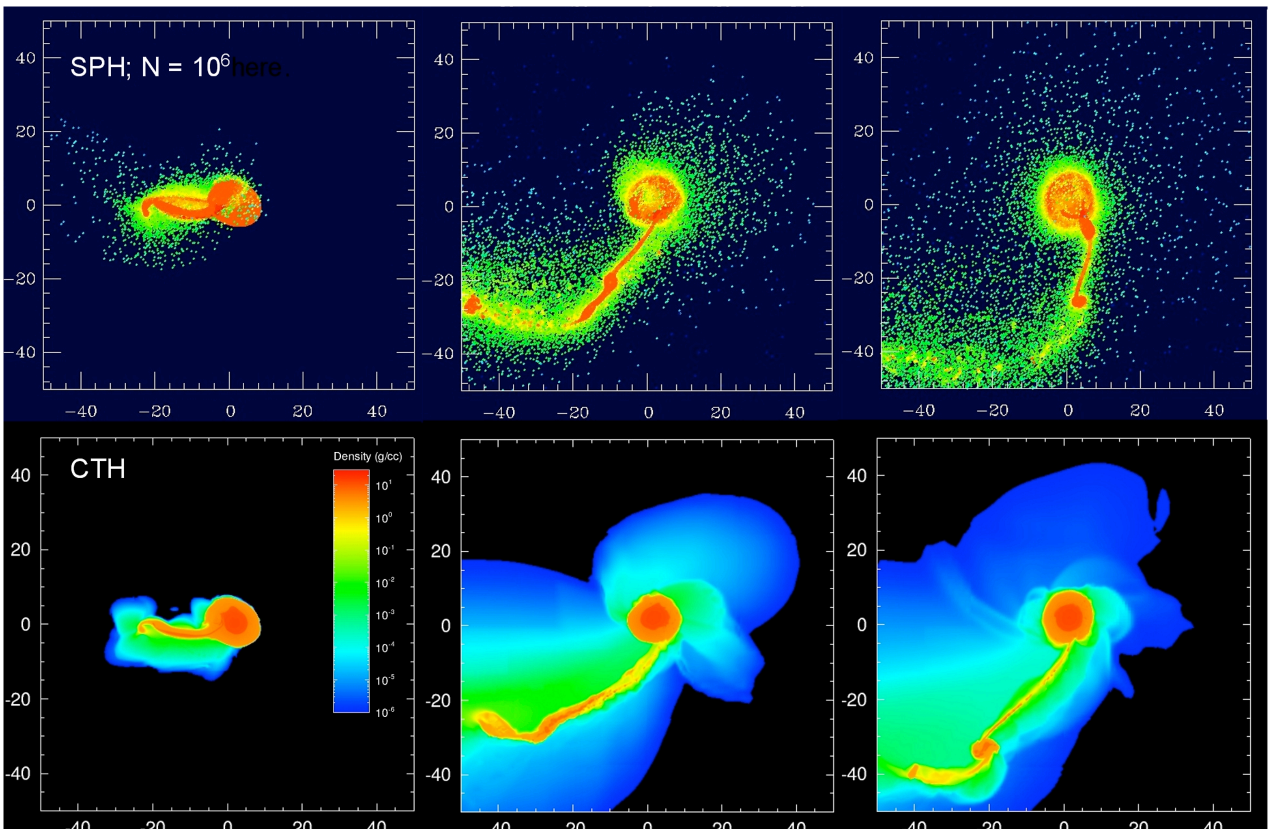


Figure 1. Simulation of a Moon-forming impact with SPH (top) and CTH (bottom). Frames from left to right show times of 1, 3.8 and 5.4 hours after the impact of a 0.13 Earth-mass impactor. Color scales with the log of material density as shown in the color bar. From Canup et al. (2012).

We have completed a new, generalized model for the thermodynamic state of the post-impact protolunar disk (Ward 2012). This model provides a full description of a two-phase, vapor-magma silicate disk in hydrostatic and phase equilibrium, including radial temperature, pressure, and density profiles as a function of the disk's gas mass fraction. We show that in the inner regions of the disk, the liquid phases will settle to the mid-plane, creating a stratified disk structure with a mid-plane magma layer surrounded by a vapor atmosphere that initially contains most of the disk's mass.

The Moon has long been thought to be highly depleted in volatiles such as water, and indeed published direct measurements of water in lunar volcanic glasses have never exceeded 50 parts per million (ppm). We have shown, however, that water can be measured in particular lunar melt inclusions

(Hauri et al. 2011; Science). These samples of primitive lunar magma, by virtue of being trapped within olivine crystals prior to volcanic eruption, did not experience post-eruptive degassing. We found that the lunar melt inclusions contain 615 to 1410 ppm water, and high correlated amounts of fluorine (50 to 78 ppm), sulfur (612 to 877 ppm) and chlorine (1.5 to 3.0 ppm). These volatile contents are very similar to primitive terrestrial mid-ocean ridge basalts and indicate that some parts of the lunar interior contain as much water as Earth's upper mantle.

We have also developed a new model for the Moon's accumulation from an impact-generated disk (Salmon & Canup 2012). Prior models predict that the Moon forms in less than a year, but they assume a disk composed of solid particles. Instead the inner disk will be a mixture of vapor and magma. In our model, we describe the disk interior to the Roche limit with a fluid treatment. Outside the Roche limit, material can accumulate into the Moon, and we describe this region with a direct N-body accretion simulation. A new finding of our work is that the Moon accretes in three phases (Figure 2). In phase 1, particles initially located beyond the Roche limit rapidly accrete until only a few massive bodies remain after a few months. The fluid disk is confined within the Roche limit by resonant interactions with outer bodies, which in turn begin to recede away from the disk. In phase 2, resonant interactions weaken as the moonlets move away from the disk and the disk is freed to spread back out to the Roche limit over several tens of years. In phase 3, new moonlets are spawned from the inner disk and collide with the Moon to finalize its accretion in ~ 100 years. This much longer formation timescale for the Moon is more compatible with a partially molten Moon and with chemical equilibration between the disk and the planet.

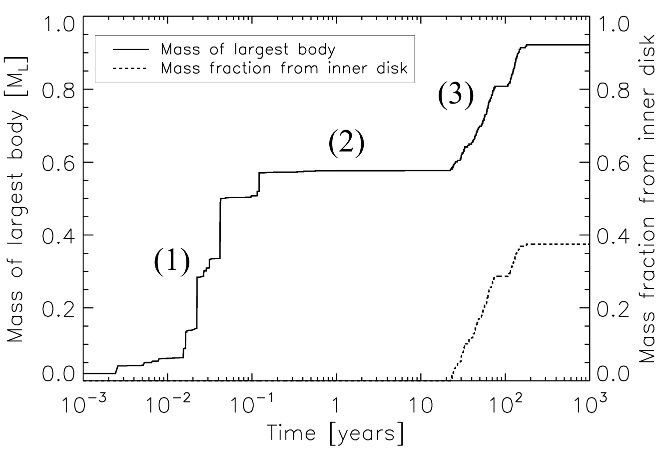


Figure 2: Results of the lunar accretion model of Salmon & Canup (2012). Mass of the moon (solid line) and fraction of its mass derived from material originating in the Roche-interior disk (dashed line). Labels indicate three accretion phases. For initial disks with 2 to 2.4 lunar masses (M_L), we find the average outcome after 10^3 years is a Moon of ~$0.8M_L$. The Moon's total accumulation timescale is ~ 10^2 years, orders-of-magnitude longer than the < 1 year timescale predicted by prior models.

We are developing a model of the Moon's temperature as it forms. The initial temperature profile in the fully assembled moon serves as the initial condition for its subsequent thermal, tectonic, and compositional evolution. In particular, constraints on the depth of the initial lunar magma ocean are key controls on the timing and duration of magma ocean solidification, the thickness and composition of the Moon's primary crust, and the abundance of water and other volatiles in the lunar interior. We have analyzed the melt produced as a function of impact properties using direct hydrodynamical simulations (Barr & Citron 2011), and have developed a three-dimensional model of the Moon's temperature as it grows due to a large number of accretionary impacts (Figure 3).

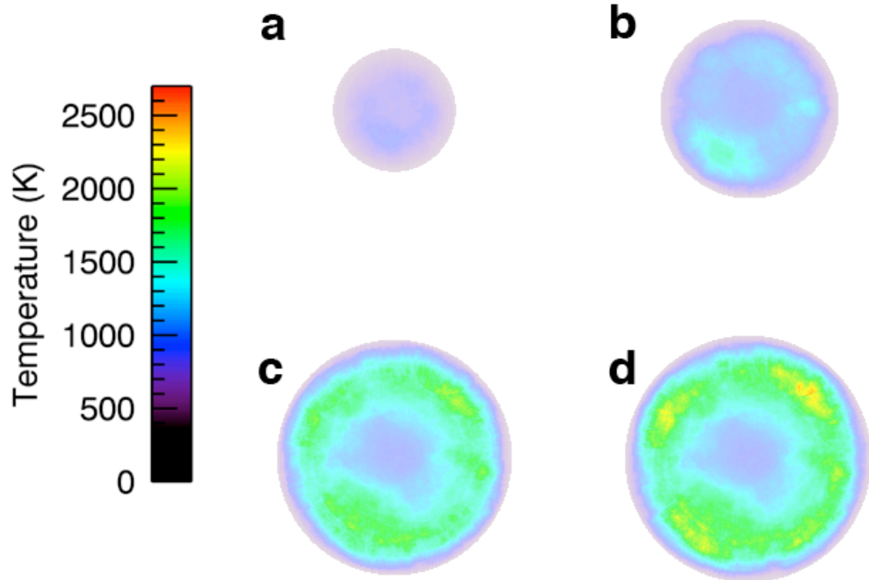


Figure 3. Example result from the three-dimensional lunar accretion model (Barr & Canup, in preparation). The Moon is represented by cubical blocks 20 km on a size. We assume a constant fraction (0.25) of the energy of each impact is retained in the Moon's interior, and distribute impact-induced heat in a sphere with a radius equal to the projectile radius that is buried 2 projectile radii beneath the surface. Impactors have a distribution of radii across the 10 km to 100 km range. Impact velocities are a function of the Moon's escape velocity, which increases as the Moon's mass increases. As the moon grows from a ~500 km radius initial "moonlet" to its final size (panels a through d in order), the temperature in its mantle increases due to the burial of impact heat. Temperatures in excess of the local melting point are achieved at a depth of a few hundred km (yellow/orange/red values), broadly consistent with an initial magma ocean.

Theme 2: Observational Constraints on the Bombardment History of the Moon

In Theme 2, we are employing inventive techniques to deduce new physical constraints on the lunar impact rate over the last 4.5 billion years. We have new results to report on our analysis of terrestrial and lunar zircons (as well as other key minerals) that are sensitive to, and have information on, the record of ancient impacts on the Earth-Moon system (Theme 2a). We have counted craters on a wide variety of lunar terrains, and we believe we have found evidence for the beginning of the lunar cataclysm on the Moon (Theme 2b). Our goal is to use lunar and meteoritic samples to establish an early lunar bombardment chronology. ***This work addresses key questions (SB-C), (DS-A), (DS-B), and (DS-C).***

Theme 2a: Bombardment Thermochronometry on the Bombardment History of the Moon

The research here has followed several broad themes that have been intimately incorporated into the research of CLOE graduate students and postdocs: (i) Impact processes in silicate crusts (Earth, Moon, asteroids); (ii) Bombardment record of the early Earth; and (iii) The thermal evolution of planetary surfaces from impacts and radionuclides. Here we briefly discuss some of the highlights of our thermal-chemical studies of impacts into the asteroid (4) Vesta, the current target of the DAWN mission, and in lunar samples.

We have investigated the thermal and temporal evolution of both Vesta and the Moon by comparative ultra-high resolution U-Th-Pb-Ti zircon depth profile analyses from the brecciated Millbillillie eucrite (Vesta) and four bulk Apollo 14 lunar samples. By searching for preserved 235-238U/207-206Pb ratios in different zircon domains (cores, mantles) within these individual crystals, we attempt to identify massive thermal events that affected them (i.e., bombardment). We are also implementing the Ti-in-zircon ([Ti]Zr) thermometer for precise estimates (independent of closure temperature (Tc)) of temperature in different mineral domains related to thermal disturbances.

If impact melt zircons or melt domains within zircons can be depth profiled to reveal distinct thermal events, these event ages can be correlated to previously reported radiometric ages for eucrites, lunar rocks and ancient terrestrial rocks to expand our knowledge of the chronology of impacts to the Moon, Earth and other inner solar system bodies. The output of this work has been a rigorous assessment of the earliest thermal records from precise U-Pb geochronology.

The samples studied so far have been:

- Apollo 14- Sample 14305. Lunar sample 14305 is a Fra Mauro breccias. This "football-sized" rock was collected about 100 m from the Apollo 14 landing site.
- Apollo 14- Sample 14311. 14311 is a coherent impact melt breccia and was one of the largest samples returned by Apollo 14.
- Apollo 14- Sample 14163. Sample 14163 is from a large bulk soil sample collected at the end of the first EVA on Apollo 14 from the area near (15 m) the LM.
- Millbillillie eucrite. Impact mixing of crustal eucrites and deeper mantle-derived diogenites produced various polymict breccias, including howardites and polymict eucrites.

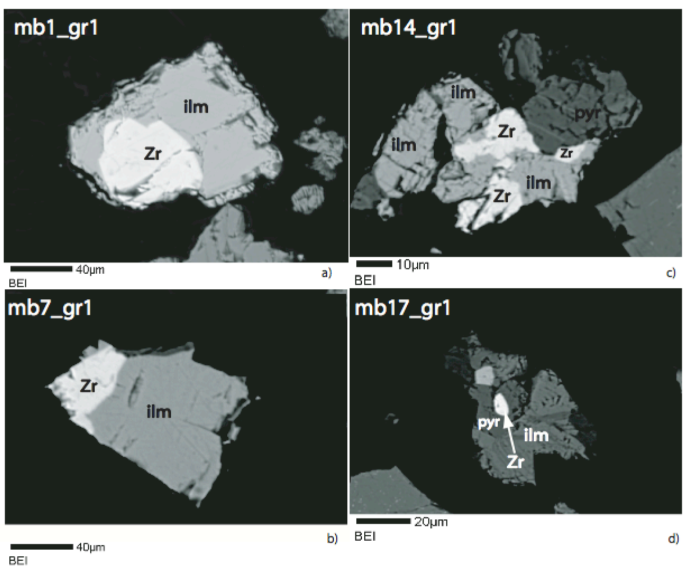


Figure 4- backscatter imaging of 4 grains from the Millbillillie eucrite; a) shows zircon grain included within an ilmenite grain; b) several fragment of zircon included within or in contact with ilmenite and pyroxene; c) zircon grain in contact with ilmenite; d) small zircon grain included within a pyroxene grain

Our work to date shows the crystallization age of basalts from Vesta (eucrites) is well constrained at ~4.56 Ga by U-Pb and 207Pb/206Pb ages from eucritic zircons, whole rock 40Ar-39Ar ages of unbrecciated eucrites, and Hf-W data. In other words, Vesta has had in intact basaltic crust from the first few years after the formation of the solar system's first solids. More interestingly, though, we have found subsequent thermal events recorded in the Millbillillie eucrites that suggests that Vesta likely was hit by large impactors very early in its history.

For example, eucritic zircon mb1_gr1 shows evidence for a thermal event with an age of ~4530 Ma. This age, ~40 Myr after initial solar system formation, statistically falls within range of proposed Hf-W model ages of the Giant Impact (GI) formation of the Moon 30-110 Myr after the formation of the first solids. Such "Moon-forming impact ages" in eucrites could mean that the same dynamical event that caused a Mars-sized impactor to hit the Proto-Earth may have also launched a wave of bodies into the inner solar system, where they could then pound on main belt asteroids. The takeaway message from this work is that Vesta may be able to constrain the last gasp of planetary accretion among the terrestrial planets.

We find the lunar zircons found in the samples above have ages that range from 4.2-4.3 Ga. This is much older than the pronounced clustering of crystallization ages in lunar impact-melt breccias at 3.9 Ga. Up to now, the lack of older ages linked directly to impact events had provided the primary evidence for a single, late cataclysmic episode of heavy bombardment. Instead, our work suggests that large, probably basin-scale impacts occurred on the Moon from 4.2-4.3 Ga. We conclude that the early bombardment of the Moon was probably made of waves, with one associated with the leftovers of terrestrial planet formation and a second one perhaps associated with the late migration of the giant planets. The apparent distribution of lunar melt breccia ages may have been strongly biased by ejecta from the formation of the 1,200 km diameter 3.8-3.9 Ga basin Imbrium.

Constraints on the timing and duration of heavy bombardments to the inner solar system has been greatly enhanced by new studies on HED meteorites and lunar impact breccias. Our near-future goal is to expand our investigations of asteroidal meteorites and lunar rocks to gain a more comprehensive picture of the impact bombardment history and dynamical evolution of the inner solar system.

Theme 2b: Relative Lunar Crater Chronology

The goals here are to analyze the Moon's cratering impact record to better understand its bombardment history, chiefly from the later portions of the Late Heavy Bombardment until the present. Research on this task is led by Dr. Clark Chapman, with primary contributions by Dr. Michelle Kirchoff, and participation by a graduate student, Kristen Sherman, and other members of the CLOE team. Additional key contributions have been made by NLSI postdoc Simone Marchi, who jointly works with both NLSI team leaders Bill Bottke (CLOE) and Dave Kring (CLSE).

Before the public release (March 2011) of the Lunar Reconnaissance Orbiter Wide Angle Camera (LRO-WAC) mosaic, Dr. Kirchoff compiled craters counts of Imbrium and Birkhoff basins from newly digitized Lunar Orbiter images. A new dataset of smaller craters within lunar basins was generated. Primary results from the analysis of these data are that small crater size-frequency distributions (SFDs) of different areas of the Moon are dominated in different and unpredictable ways by secondary craters and the shape of the SFD changed between the formation of Birkhoff (> 4 Gyr) and Imbrium (4 < age < 3.5 Gyr). These results agreed with our new look at some historic data published by Wilhelms (Geological History of the Moon, 1987), which sparked some discussion with Dr. Marc Norman and other CLOE scientists about lunar bombardment history in the light of recent insights into the dynamics of impactors in the solar system, such as the "Nice model." A primary conclusion, however, was that the data from older imaging is inadequate and further insights would require new data from upgraded imaging like the LRO-WAC mosaic.

After the arrival of the LRO-WAC mosaic (March 2011), we began in earnest the heart of this task, which is to compile size-frequency distributions (SFDs) of small craters (diameter, D < 10 km) superposed on the floors of numerous mid-sized (D = 80-100 km) craters at random locations and of various ages. Dr. Kirchoff, along with a graduate student, Kristen Sherman, has compiled the superposed crater SFDs for about half of our initially selected mid-sized craters. From these data the absolute age of the floors have been computed in collaboration with Dr. Simone Marchi, using his developed Model Production Function (MPF) for the impact flux (Marchi et al., AJ 137, 4936-4948).

One preliminary result of this work is that in comparing our SFD's to the MPF SFD, which is generated from numerical modeling of impactor populations, not observations, we find many matches. This implies many of our small crater populations are not composed of secondary craters, but primaries, which is important to know when using the superposed crater SFDs to understand surface ages and trends suggested by the SFDs. Another interesting result is that the shape of the small crater SFD has likely changed with time. Specifically, the SFDs appear to be losing their largest craters (D ~ 2-10 km) as the floors get younger. This is a consequence of a reduced flux of impactors of corresponding size. Future work by Dr. Bill Bottke will model numerically the how the impactor source is depleted over time to gain a better understanding of evolution of impactor populations. Finally, we have found that the range of our cumulative crater densities for the crater floors (factor of 15) is smaller than expected compared to the range found traditionally for large craters between the lunar highlands and maria (factor of 20), especially given that the age range is larger for our data set (~ 3 Gyr vs. ~2 for highlands and maria). A likely explanation for this is the impact rate for small lunar craters ($D < 1$ km) has declined more slowly than for the large ones.

We conclude this section by describing the exciting work recently published by Dr. Marchi. It is well known that the earliest bombardment history of the Moon provides powerful constraints for solar system evolution models. A major uncertainty, however, is how much of this history is actually recorded in lunar craters. As described above, some argue that most ancient lunar craters and basins were produced by a declining bombardment of leftover planetesimals produced by terrestrial planet formation processes. Others believe that most lunar craters and large basins were formed in a narrow time interval between 3.8 and 4.0 Ga, the so-called lunar cataclysm. We asked whether it was possible that contributions from both scenarios could be represented in the lunar crater record. If so, when did the declining bombardment end and the lunar cataclysm begin?

In Marchi et al. (2012), we showed, using new counts of 15–150 km diameter craters on the most ancient lunar terrains, that the craters found on or near the 860 km diameter Nectaris basin appear to have been created by projectiles hitting twice as fast as those that made the oldest craters on various Pre-Nectarian-era terrains. This dramatic velocity increase is consistent with the existence of a lunar cataclysm and potentially with a late reconfiguration of giant planet orbits, which may have strongly modified the source of lunar impactors. This work also suggests that the lunar cataclysm may have started near the formation time of Nectaris basin. This possibility implies that South Pole-Aitken basin (SPA), the largest lunar basin and one of the oldest by superposition, was not created during the cataclysm. This view is strengthened by our interpretation that a substantial fraction of ancient craters on SPA were made by low velocity impactors.

Theme 3: Determining Lunar Impact Rates

Once the surface of the Moon solidified, it mainly has been shaped by impacts. As a result, the surface of the Moon stands as a witness to the late stages of planet formation and the evolution of the planetary system as a whole. Indeed, since it is nearby and accessible by spacecraft, the surface of the Moon probably represents the best record we have of the early Solar System. Conversely, we cannot understand the Moon until we understand this history.

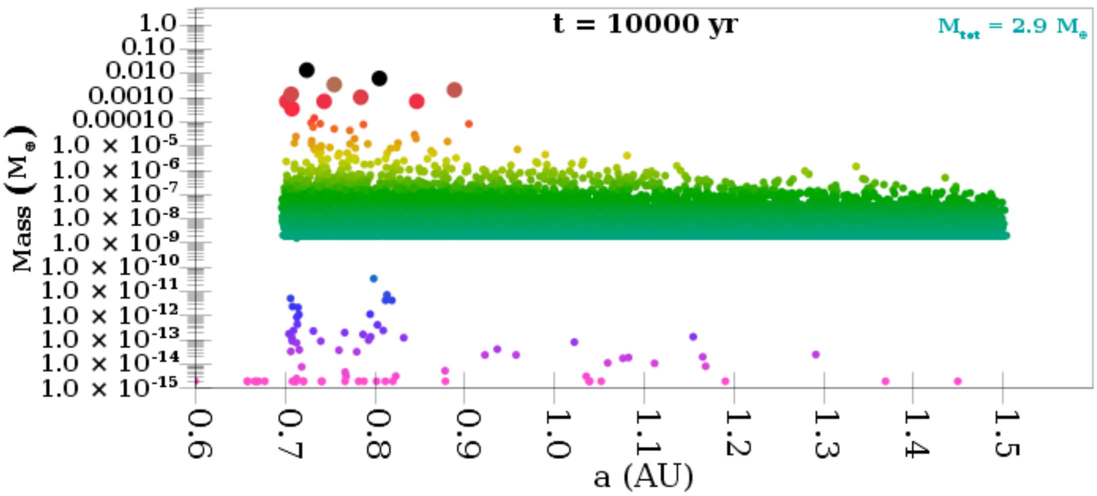
The goal of Theme 3, therefore, is to construct the most complete theoretical models of the impact history on the Moon based on new dynamical models of the Solar System. **Here we address questions (SB-C), (DS-A), (DS-B) (DS-C), and (DS-D) from above.**

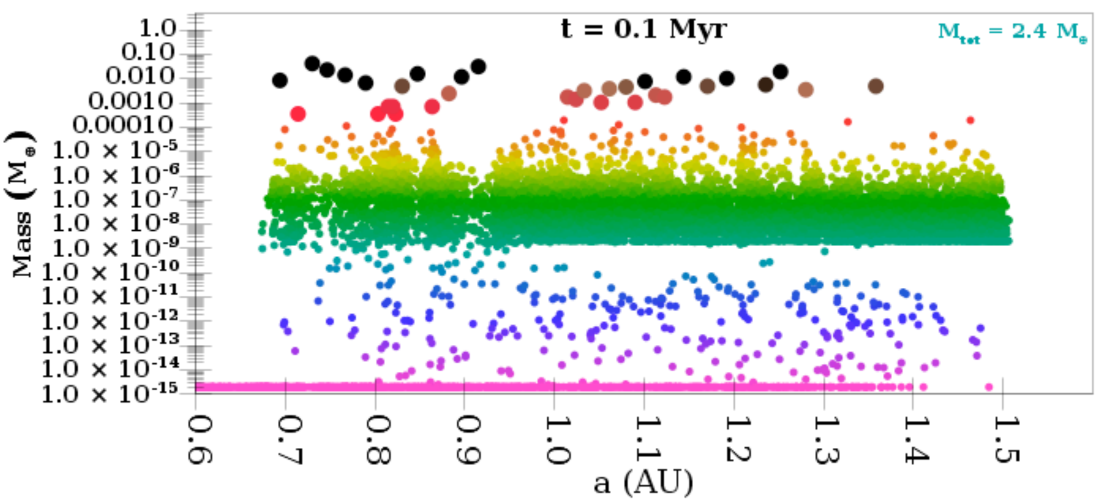
Theme 3a. Understanding Planet Formation In Order to Constrain the Moon's Earliest History

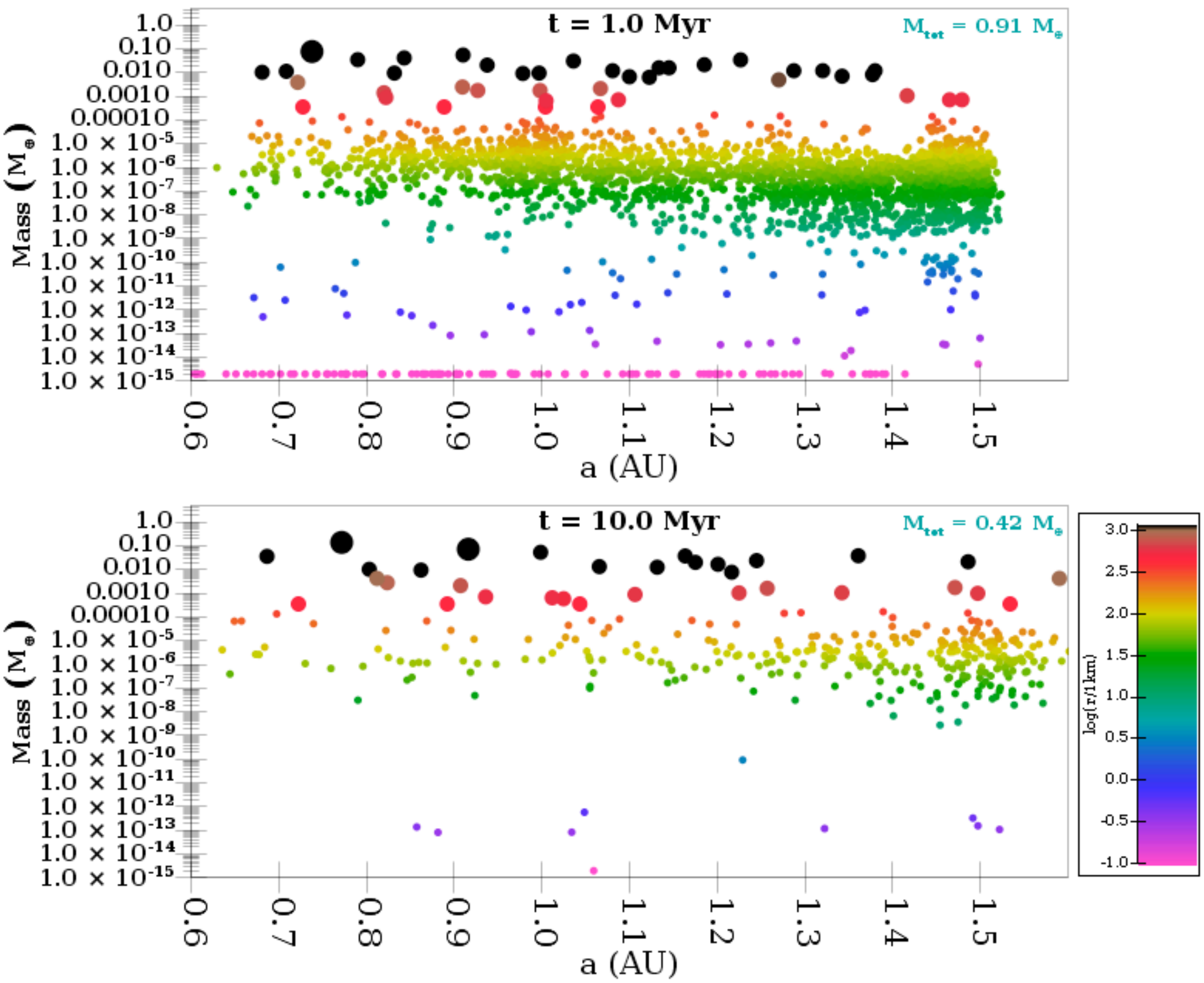
Over the last three years we have been perusing a multi-prong approach to this effort - each prong designed to investigate different areas of the problem.

On the most basic level, we have now constructed the most advanced code to date to study the end-to-end process of planet formation. We refer to it as the <u>*Lagrangian Integrator for Planetary Accretion and Dynamics*</u> or *LIPAD* (Levison et al. 2012). LIPAD is built on top of our fast symplectic N-body integrator. In order to handle the very large number of planetesimals required by planet formation simulations, we introduce the concept of a *tracer* particle. Each tracer is intended to represent a large number of disk particles on roughly the same orbit and size as one another. We developed statistical algorithms that follow the dynamical and collisional evolution of the tracers due to the presence of one another. The tracers mainly dynamically interact with the larger objects *(planetary embryos)* in the normal N-body way. LIPAD's greatest strength is that it can accurately model the wholesale redistribution of planetesimals due to gravitational interaction with the embryos, which has recently been shown to significantly affect the growth rate of planetary embryos (Levison et al. 2010).

We have begun to use LIPAD to study terrestrial planet formation. For example, Figures 5a-d shows four snapshots of the mass of growing planets in a system originally containing 3 Earth-masses of 10 km planetesimals. Although these simulations are on-going, we have already found significant differences with previous works. First, as the figure shows, gaps open around the planets, stifling their growth. Also, the planetesimals collide with one another, effectively causing the them to grind away. At the end of the simulation the system contains only 0.4 Earth-masses of material - too little to make the observed planets! We are currently varying free parameters, like the mass of the disk, to determine under what conditions we can reverse this startling result.







Figures 5a-d. *Four snapshots of the mass of growing planets in a system originally containing 3 Earth-masses of 10 km planetesimals. For the first time ever, collisions and dynamics have been combined within a single model that allows both to affect one another while* _simultaneously_ *performing the dynamics correctly according to a N-body code. The results are quite different from the standard model, and they suggest we have been missing some big things in our understanding of planet formation.*

In the work submitted in Minton & Levison (2012), we addressed a long standing problem in studies of the formation of the terrestrial planets, namely the small mass of Mars. In this work we show that the small mass of Mars is well explained by the addition of planetesimal-driven migration (PDM) to models of planetary embryo formation. In our model, Mars initially forms as one of several Moon-mass embryos inside of ~1AU. After the onset of PDM, the proto-Mars migrated to ~1.5 AU and gained most its full mass, leaving behind a wake of excited planetesimals between ~1--1.5 AU. The excited planetesimals collisionally grind and lose mass, leaving Mars isolated from late stage embryo-embryo mergers, which only occur inward of ~1 AU. This model has wide ranging implications for not only the formation history of Mars, but also the distribution of small bodies left over from the epoch of terrestrial planet formation. Knowledge of these remnant small body reservoirs are distributed will help understand the early bombardment history of the Moon.

The time immediately after the Moon's formation is also of great interest to us. Consider that core formation should have stripped the terrestrial, lunar, and martian mantles of highly siderophile elements (HSEs), which consist of gold, platinum, and other rare metals. Instead, each world has disparate, yet elevated HSE abundances. Late accretion may offer a solution, provided that ≥0.5% Earth masses of broadly chondritic planetesimals reach Earth's mantle and that ~10 and ~1200 times less mass goes to Mars and the Moon, respectively. In Bottke et al. (2010), which was published in *Science*, we showed that leftover planetesimal populations dominated by massive projectiles can explain these additions, with our inferred size distribution matching those derived from the inner asteroid belt, ancient martian impact basins, and planetary accretion models. The largest late terrestrial impactors, at 2500 to 3000 km in diameter, potentially modified Earth's obliquity by ~10°, whereas those for the Moon, at ~250 to 300 km, may have delivered water to its mantle. These are all exciting results, and we are currently testing these ideas with new modeling and sample analysis efforts.

Theme 3b. Understanding Both Giant Planets Migration and the Nature of the Late Heavy Bombardment

The Late Heavy Bombardment (LHB) is an epoch that ended about 3.8 Gy ago with the formation of the lunar basins Imbrium and Orientale. While the exact events that led to their formation still remain a mystery, there seems to be little doubt that impactors were raining down on the Moon and other solar system at this time.

It has been argued that the LHB could have been set into motion by the rearrangement of orbits of the outer giant planets. According to this popular idea, known as the Nice model, the lunar basin impactors have origin in the asteroid belt region and trans-Neptunian disk of comets that were sent into the inner solar system by wandering outer planets. Note that we find the Nice model compelling because it can quantitatively explain the orbits of the Jovian planets, the capture of comets from the primordial disk into several different small body reservoirs in the outer solar system (e.g., Trojans of Jupiter and Neptune, the Kuiper belt and scattered disk, the irregular satellites of the giant planets, and the outer asteroid belt). These accomplishments are unique among models of outer solar system formation.

To further test the Nice model scenario, and precisely how it should work, we conducted computer simulations to determine (1) the evolution of planets in the Nice model (Nesvorny 1011, Nesvorny et al. 2010), and (2) the accretion rates of micrometeorites during the LHB. The LHB is of fundamental interest in studies of the origin of life because it immediately precedes the oldest evidence for a biosphere. The significance of (2) in this context is that micrometeorites can bring in unaltered primitive material from the outer solar system. They could potentially be the source of the earliest organic material that gave rise to life on Earth.

We found that the Nice model simulations starting with four giant planets have a low success rate in matching the present orbits of giant planets, and various other constraints (e.g., survival of the terrestrial planets). The dynamical evolution is typically too violent (particularly if Jupiter and Saturn start in the 3:2 resonance) and tends to lead to final systems with fewer than four planets.

Our best results were obtained when assuming that the Solar System initially had five giant planets, with one ice giant, with a mass comparable to that of Uranus and Neptune, ejected to interstellar space during the LHB. This possibility appears to be conceivable in view of the recent discovery of a large number of free-floating planets in interstellar space, which indicates that planet ejection should be common. Thus, our work may suggest the starting conditions for the Solar System were wildly different than they are today.

We are also studying the implications of the Nice model on asteroid belt. For example, it has been proposed that resonance sweeping by late giant planet migration may be a plausible mechanism for producing pre-mare lunar craters and an apparent "spike" in the impact ages measured in samples of the Moon recovered during the Apollo and Luna missions (Levison et al. 2001; Gomes et al. 2005; Strom et al. 2005; Minton & Malhotra 2009). In the work presented in Minton & Malhotra (2011), we calculated the eccentricity excitation of asteroids produced by the sweeping nu6 secular resonance during the epoch of giant planet migration in the early history of the Solar System. We found that the asteroid belt would not have survived if migration were too slow, <~ 4 AU/My. This migration rate is significantly faster than estimated rates from work on smooth planetesimal-driven migration of giant planets (Hahn & Malhotra 1999, 2005; Murray-Clay & Chiang 2005). On the other hand, is it consistent with a subset of the Nice model. In all cases where the asteroid belt survived, it was only depleted by roughly half --- a factor too small to account for all lunar basins. Thus, we apparently need another source for the impactors that caused the lunar basins.

The search for the missing impactors led to a unexpected but highly compelling source. Many assume the barrage of comets and asteroids that produced many young lunar basins ended across the solar system about 3.7-3.8 Ga with the formation of Orientale basin. Evidence for LHB-sized blasts on Earth, however, tend to extend into the Archean and early-Proterozoic (i.e., 1.8-3.7 Ga). They take the form of impact spherule beds, globally-distributed ejecta layers created by Chicxulub-sized or larger cratering events: at least 7, 4, and 1 have been found between 3.23-3.47-Ga, 2.49-2.63 Ga, and 1.7-2.1 Ga, respectively.

Using new numerical work, we used the above impact spherules to show that the LHB lasted much longer than previously thought, with most late impactors coming from the “E-belt”, an extended and now largely extinct portion of the asteroid belt between 1.7-2.1 AU. This region was destabilized by late giant planet migration according to the results of the Nice model described above. E-belt survivors now make up the high inclination Hungaria asteroids. Scaling from the observed Hungarias, we find E-belt projectiles made ~10 lunar basins between 3.7-4.1 Ga. They also produced ~15 Archean-era basins on Earth between 2.5-3.7 Ga, as well as ~70 and ~4 Chicxulub-sized or larger craters on the Earth and Moon, respectively, between 1.7-3.7 Ga. These rates reproduce impact spherule bed and lunar crater constraints. This work is being published by Bottke et al. (2012) in an upcoming issue of Nature.

Community and Professional Development

CLOE is working to achieve NLSI's goal of training the next generation of lunar scientists through the following means.

First, CLOE is actively fostering graduate-level education and post-graduate career development. For example, Dr. David Minton accepted an Assistant Professor position at Purdue University, and Dr. Amy Barr became a new faculty member of Brown University. At present, we have several postdocs: Dr. Julien Salmon and Dr. Channon Visscher, both who work with Dr. Robin Canup on Theme 1, Dr. Michelle Kirchoff, who is working with Clark Chapman on Theme 2, Dr. Kevin Walsh from the University of Arizona, who is working with Hal Levison on Theme 3, and Dr. Simone Marchi, who is working with Dr. William Bottke (and Dr. Dave Kring from CLSE) on Theme 3. We also have several graduate students from the University of Colorado: Robert Citron completed his work with Amy Barr on Theme 1, Michelle Hopkins and Elizabeth Frank are continuing to work with Prof. Steve Mojzsis on Theme 2, and Kristin Sherman has completed her work with Dr. Clark Chapman on Theme 2.

Second, we are teaching classes at CU on the Moon. PI William Bottke team-taught a graduate level class at the University of Colorado with fellow NLSI PI’s Mihaly Horanyi and Jack Burns on Interdisciplinary Lunar Science in the Spring 2010. Approximately 15 students attended the class. The class website can be found at at http://lunar.colorado.edu/~jaburns/astr5835/. The class covers three broadly defined areas of lunar science:

- ***Of the Moon:*** Investigations of the nature and history of the Moon (including research on lunar samples) to learn about this specific object and thereby provide insights into the evolution of our solar system
- ***On the Moon:*** Investigations of the physics of the lunar surface, including its interactions with the solar plasma and UV radiation. Existing dust and plasma observations and the new ideas for future surface experiments.
- ***From the Moon:*** Use of the Moon as a platform for performing scientific investigations, including observations of the Earth and the wider cosmos that are uniquely enabled by being on the lunar surface.

In addition, Co-I Mojzsis and psotdoc Walsh have also been actively engaged in the teaching mission of CLOE, with a new graduate seminar class that was offered both in the Fall semester 2010 and Spring 2012 on the topic of Planetary Water (origin of water to planets), and The Moon (a new graduate course offered in Planetary Sciences). The syllabus for "The Moon" can be found at http://isotope.colorado.edu/~geol5700/Course%20Outline.pdf. Note that many members of CLOE have given guess lectures in the class (e.g., Bottke, Canup, Minton, Chapman, etc.), which gives us even more opportunity to interact with students.

Finally, we have been actively working to communicate our new work in a number of different forums. Dr. William Bottke combined forces with Dr. Dave Kring (CLSE) to sponsor the Workshop on Early Solar System Bombardment II at the Lunar and Planetary Institute in Houston, TX. CLOE has participated in numerous department seminars as well as conferences (e.g., AGU, DPS, LPSC, Lunar Science Forum). As part of this, in 2009-2010, SwRI donated funds and office space to CLOE so they could construct a high definition videoconferencing system within a 30 person conference room at SwRI-Boulder. This conference room has already been used for many CLOE team meetings as well a public broadcast video-seminar on solar system bombardment by Dr. Hal Levison and Dr. Steve Mojzsis. CLOE has also been working closely with high school students from the Denver School of Science and Technology and now Denver North High School to construct an interactive website (http://cloe.boulder.swri.edu/) that will ultimately serve many purposes: it will show off why the Moon is interesting in a manner young people can understand while also serving as a working website for CLOE scientists to show off their results to one another. We encourage the reader to explore this website. Last, but not least, Dr. Chapman, as Deputy Director of CLOE, is serving as CLOE's representative on the NLSI Media Working Group and participated in the Group's first telecon early in 2010.

Education and Public Outreach

CLOE is enthusiastic about sharing the excitement of our lunar research through a cohesive program, led by Dr. Stephanie Shipp (Manager of E/PO at LPI). Our highlights are:

- CLOE E/PO efforts have concentrated on creating partnerships and leveraging existing networks to build sustainable E/PO programs with national reach in lunar science and exploration. To this end, a suite of programs has been developed in collaboration with strategic partners: 1) a high school research project integrated into the Summer Science Program; 2) products and training to enable librarians to engage the public in lunar science and exploration; and 3) a public website designed and maintained by high school students.

- The CLOE Team partnered with the Summer Science Program (SSP) to develop and implement a two-day authentic research project based on CLOE science objectives that allows participation in NASA science activities, inspires interest in science and science careers, and enhances science skills. One-hundred and forty four academically gifted high-school students have participated over two years, with an additional 72 taking part in Year 4.

- In partnership with the Explore library program and six state library systems, the CLOE team created resources and provided training to support librarians in engaging their patrons in lunar science and exploration. Over 80 librarians have been trained to date. Through their children's and family programming, they are sharing CLOE and NLSI science with an estimated 5000 patrons. An additional 90 will be trained in Year 4.

- The CLOE website is a portal to engage the public and increase the public's understanding of science that has been developed and maintained in partnership with high-school students. Through their eyes the science, scientists, and events and activities of CLOE, NLSI, and NASA are shared with the public.